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Tensile Mechanics of the Developing Baboon Cervical Spine

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ABSTRACT

This study examined the effect of spinal development (developmental age) on the tensile mechanics of the cervical spine. Isolated functional spinal units were subjected to tensile loading to document their mechanical response (tensile stiffness and ultimate failure load). Cadaveric baboon specimens were used due to the limited availability of human tissues in the pediatric age range. Statistically significant correlation was found between developmental age and both tensile stiffness and ultimate failure load suggesting that scaling relationships between the adult and the child spine exist. Further, differences in these properties were observed as a function of spinal level. In addition to providing age-related data for the developing spine, our findings suggest that reasonable scaling relationships exist between the adult and the child spine. These relationships provide a basis for scaling adult properties to the child, which may abet the development of pediatric neck injury thresholds.

INTRODUCTION

Neck injury patterns associated with air bag related fatalities in children suggest that tension is one of the mechanisms causing these injuries. This study examined the effect of spinal development on the tensile mechanics of isolated cervical functional spinal units (FSUs). Given the limited supply of human pediatric tissues, cadaveric baboon (Papio anubis) spines were selected for testing based on their similar comparative and functional anatomy to the human (Swindler and Wood, 1973). The baboon cervical functional spinal units tested ranged in human equivalent age from 2.5 to 18 years. The specific hypotheses tested by this study were: *(i) Tensile mechanics (ultimate failure load and stiffness) for functional spinal unit are correlated to developmental age; and (ii) Tensile mechanics vary by spinal level across all age groups.*

METHODS

Eleven, fresh (unembalmed) cadaver baboon spines were obtained through the Washington Regional Primate Research Center. These specimens were euthanized for unrelated short-term (6-8 week) research projects which should not have had any effect on musculoskeltal properties. All 11 specimens collected were males to preclude gender differences. In order to relate our findings to human development, a human-equivalent age was established for each specimen using a skeletal maturation index based on radiographic assessment (Hassel and Farman, 1995; Kuhns, 1998). This resulted in an overall sample age range of 2.5 to 18 in human-equivalent years.

Specimen Preparation

Each specimen was inspected for previous injury or spinal pathology and dissected free of all musculature leaving the full intact osteoligamentous cervical spine. The cervical spine specimen was then further dissected into four functional spinal units (FSUs): Occiput-C2, C3-4, C5-6, C7-T1. Coronal and sagittal plane radiographs, as well as axial computed tomographs (CTs), were taken of each specimen to make gross measurements and define specimen skeletal maturity. In preparation for testing, the free ends of each FSU specimen were wired and then potted in poly-methylmethacrylate.

Experimental Procedure

Experimental testing was performed using an MTS (Model 858 Bionix, MTS Corp., Eden Prairie, MN) servohydraulic testing system to perform tensile loading at 0.5-mm/sec. The potted inferior vertebra was secured to a six-axis load cell and the superior vertebra was attached to the ram via a universal joint providing fixed-free end conditions. Each specimen was preconditioned 5 cycles to 40% of body weight (Panjabi et al., 1978) at death, and then held at this load for 3-minutes to examine the creep response for a separate study. Following non-destructive testing, the specimen was pulled to failure in tension at 0.5-mm/sec. The inferiorly mounted six-axis load cell measured the force/moment response from a pure tensile input and the displacements were recorded using an LVDT. These data were collected at 200-Hz using LabVIEW (National Instruments, Austin, TX) data acquisition software.

Data Analysis

The ultimate tensile failure load and stiffness were determined directly from the measured load-displacement data. The failure load was established as the maximum load on the load-displacement curve and the stiffness was computed as the slope of the linear portion of that relationship. A linear regression analysis was preformed to determine correlation between these properties and human-equivalent age. An ANOVA was then performed to establish significance of the above correlations. Due to our small sample size and unbalanced matrix, post-hoc tests (Tukey) were performed to compare differences in the properties between spinal levels as a function of age. While the statistics utilized continuous data, the developmental specimens were grouped into four categories for observational purposes and scaling (Tab.1).

Table 1. Grouped Specimen Data.

Category	Mean Age (human-equiv years)	Sample Size
3	2.8	2
6	7.0	3
12	11.2	3
Adult	16.3	3

RESULTS

Across all spinal levels, both the ultimate tensile failure load ($r = 0.722$, $p = 0.001$) and the tensile stiffness ($r = 0.638$, $p < 0.001$) were found to be significantly correlated with age. When plotting these data by spinal level (Figs. 1 and 2), level-specific differences in mechanics (stiffness and failure load) were observed. These differences were statistically significant ($p < 0.05$) when comparing the ultimate failure load of the upper cervical spine (Oc-C2) against the lower FSUs. For stiffness, significant level differences were observed between the mid-cervical (C3-4 and C5-6) and the Oc-C2 and C7-T1 FSUs.

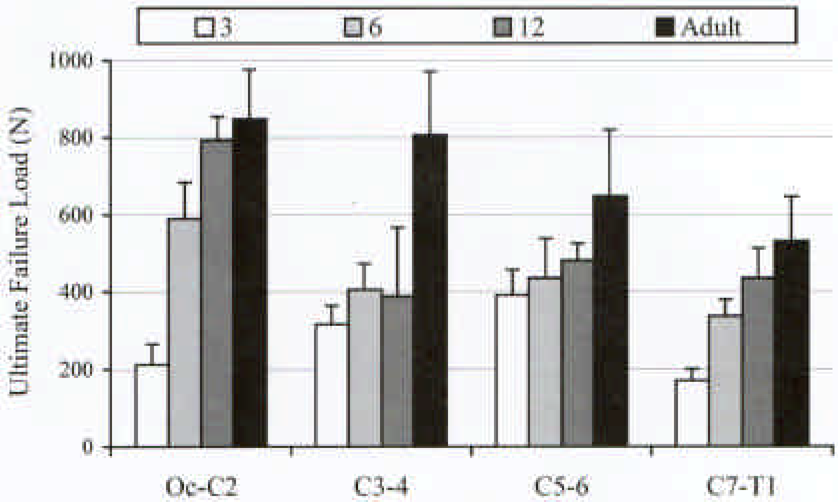

Figure 1. Ultimate tensile failure load by spinal level (grouped by age).

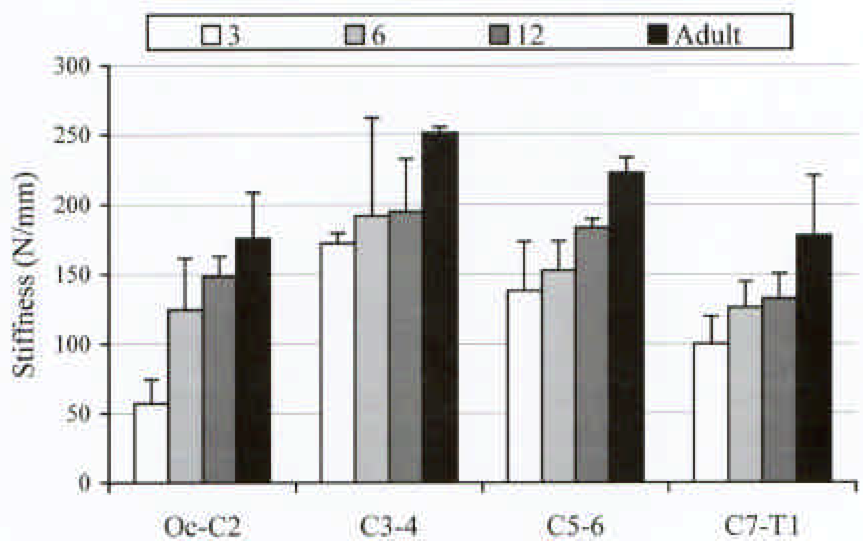

Figure 2. Tensile stiffness by spinal level (grouped by age).

Post test inspection of the specimens revealed that, without exception, the tensile failures occurred through the physis (growth plate) in the lower FSUs, and ligamentously between the C1-2 vertebrae in the upper FSU. Scaling relationships between the developing spine and the adult were obtained by grouping the data by age and normalizing the grouped mean values to the adult (Figure 3).

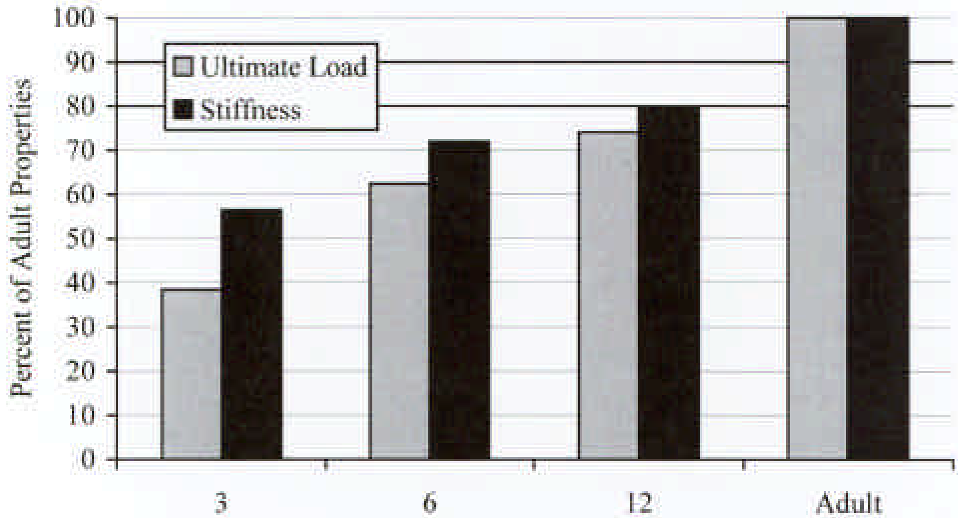

Figure 3. Scaling relationships (child-to-adult) based on tensile mechanics.

DISCUSSION

In this study, the tensile mechanical properties (stiffness and ultimate failure load) of isolated FSUs were measured and correlated with age. These data clearly demonstrate age-related differences in the tensile mechanics of the developing spine in support of hypothesis (i). Moreover, significant differences were observed in the mechanics of functional spinal units along the length of the spine supporting hypothesis (ii). These level-specific differences in tensile mechanics show that in addition to increasing stiffness and failure load with age at each spinal level (Oc-C2, C3-4, C5-6, C7-T1), there were distinct differences in properties between levels.

When examining the level-specific differences, the highest stiffness values across all age groups were found at the C3-4 level with the lowest at either Oc-C2 or C7-T1. A decreasing trend in tensile failure load was observed when moving from the upper cervical spine to the lower for each spinal level except for the youngest age group (3 y.o.). For this age group, there was an indistinguishable difference in failure load between the highest (Oc-C2) and lowest (C7-T1) FSU level, which would indicate an equal risk for tensile failure. These results are consistent with previously reported injury data and may help to explain why upper cervical spine injures are seen in the young pediatric age range and are much less so in the adult (McGrory, 1993).

For each specimen tested, the failure was directly through the growth plate and revealed a relative strength of the superior physis as failures in the inferior growth region were predominant. These tissue failure findings and the failure load patterns are consistent with epidemiological data indicating that these experimental methods are relevant for examining pediatric tensile injuries.

In addition to providing age-related data for the developing spine, our findings suggest that reasonable scaling relationships exist between the adult and the child spine. These relationships may provide a basis for scaling human adult properties to pediatric age range.

CONCLUSIONS

Additional studies will be required to relate baboon mechanical properties to the human. Nevertheless, this study provides an important perspective of the age-related tensile mechanics associated with the developing spine.

ACKNOWLEDGEMENTS

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